2 April, 2015

Report from the 3rd Meeting of the PIP-II Machine Advisory Committee (P2MAC)

March 9-11, 2015
Fermilab

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1. Introduction

The PIP-II Machine Advisory Committee is the new name of the former XMAC, reflecting the replacement of Project X by PIP-II. It held its third meeting on March 9-11, 2015, at Fermilab.

All Committee members except Rick Baartman (TRIUMF) were present, namely: Roland Garoby (ESS - chair), Frank Gerigk (CERN), Kazuo Hasegawa (JAEA, J-PARC), Sang-Ho Kim (ORNL, SNS), Deepak Raparia (BNL), Jie Wei (MSU, FRIB), Hans Weise (DESY).

The P2MAC is grateful to the speakers for the quality of their talks and to the organizers and the Fermilab management for the quality of the organization. The availability before the meeting of the slides and of the written reactions to the previous recommendations helped preparation by the committee members.

The Committee responses and main recommendations are included in the executive summary (section 2). The findings and observations, which lead to these recommendations, are detailed in the second part of this report (section 3). This last part also contains additional recommendations concerning the linac design.

2. Executive summary

PIP-II goals, strategy and status

Since its presentation last year to the Committee, the PIP-II concept has been scrutinized during the P5 process. The outcome has been a strong endorsement by P5 in its Recommendation 14: "**Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.**"

In the longer term, the leading experimental opportunity identified by P5 is an upgrade of the Mu2e experiment that requires a continuous beam at intermediate energies. Moreover, PIP-II should also provide the possibility to progress towards higher beam power from the Main Injector.

A complete draft of the PIP-II Reference Design Report has been released, in view of final publication in 2015. The organization of Fermilab has been adapted to the two priorities of fulfilling responsibilities in LCLS-II and preparing for PIP-II. The work programme of PIP-I has been integrated in PIP-II. The participation of the Indian DAE has been secured through the signature of an Annex with the DOE.

An extensive R&D programme is taking place for the linac. It will materialize in 2015 with the installation of the RFQ in the PXIE test place, the vertical test of HB650 cavities and the test of Indian-built solid-state RF amplifiers.

CD-0 is expected to be passed in the near future. It will be followed by 8 years of development and construction, leading to the end of the upgrade of the Fermilab accelerator complex in 2024, when the LBNF experiment will start taking data.

Comment

- The Committee acknowledges and fully agrees with the merge of PIP-I into PIP-II, with the associated reduced investments in the present linac.
- The Committee takes note that the need to prepare the possibility in the long term to operate the linac in CW is formally confirmed and is an integral part of PIP-II.
- The R&D on linac components is productive and will properly demonstrate the capability and commitment of the Indian partner.

Q1: Design Concept: Does the PIP-II conceptual design represent a viable concept for a high intensity proton facility meeting the enumerated performance goals?

PIP-II is tailored to minimize cost, re-using and boosting the performance of the Booster, Recycler and Main Injector. Adequate progress in the performance of these existing machines and their reliable operation is crucial.

The on-going R&D is meant at providing confidence to get the expected beam characteristics from the linac when construction will start. However, the efforts required to reach the necessary performance with the existing machines shall not be underestimated. The responses to Recommendations 5, 6 and 7 in the 2014 Committee report show that work on these subjects is not sufficient. These Recommendations are therefore re-formulated in the following part of the present report.

Q2: R&D Program: Is the R&D plan properly directed at addressing the identified technical and cost risks in an effective manner?

- 'The purpose of the R&D program is to mitigate technical and cost risks, by validating the choices made in the PIP-II facility design and by establishing fabrication methods for major subsystems and components, including the qualification of suppliers.'

- The technical risk studies for the linac concentrate on the PXIE front end and on the SRF development. Beyond demonstrating the operation of the low energy accelerating structures, PXIE will also allow testing other equipment like RF amplifiers and LLRF, beam instrumentation. The planning for building and testing the higher energy accelerating structures (SSR1 and 2, LB650, HB650) is matched to the goal of starting construction in 2019.

- Technical risks for the rings are non-negligible. The possibility to reliably accelerate 50% more intensity per pulse in the booster with bunches of reduced emittance of 0.08 eVs remains to be demonstrated, either through specific experiments or by simulation. The same question applies to the MI, which is also expected to reliably accelerate 50% more intensity per pulse.

R1: Perform a comprehensive beam dynamics analysis to identify performance-limiting mechanisms and parameters including the effects of space charge, wall impedances and electron cloud in the Booster, RR and MI.

R2: Assess Booster transition-crossing performance with benchmarked simulation codes.

- Performance of slip stacking in the RR with 50 % more beam intensity and at constant beam loss power is a major uncertainty. ESME based simulations shall be used with caution, due to the lack of clarity of the employed algorithm.

R3: Demonstrate with realistic simulations that slip stacking in RR at high intensity can be achieved with an acceptable loss budget. Identify the resulting requirements for equipment and for the beam from the Booster.

R4: Identify and exploit a code of higher quality than ESME. Else trigger the development of a better code jointly with other concerned laboratories (CERN, SNS, J-PARC, GSI, BNL …).

Q3: R&D Program: Are the risks appropriately prioritized and will the completion of the R&D plan provide a basis for proceeding to the construction phase with confidence that performance goals can be met?

- The technical risks for the linac are satisfyingly prioritized. The completion of the R&D will give the necessary input for proceeding to construction with confidence of reaching the expected performance.

R5: Use PXIE to debug the combined operation of systems. This will save time during the actual PIP-II commissioning.

- The technical risks for the rings deserve more attention (recommendations R1-4 above).

- The integration of in-kind contributions increases risks and requires additional coordination effort. A proper definition of interface requirements is especially important. The strong dependence on a single collaboration partner entails specific schedule risks.

R6: Develop strategies to reduce the risk related to large in-kind contributions.

R7: As a test case, analyze and follow the risk (technical & schedule) for the Horizontal Test Stand set-up.

- PIP-II System Engineering and Integration is intended to enforce the use of the FNAL Engineering Manual for improving all engineering practice. This integrated design approach is important to follow-up equipment all along the lifetime of the facility and to optimize quality.

R8: The Committee is convinced of the importance of System Engineering and Integration and strongly encourages a proper implementation. Early agreement on this practice with partner laboratories will be essential for the in-kind contributions from international collaborators.

- A project wide coordination of activities is required to identify meaningful passive measures to reduce vibrations of accelerating structures to a reasonable level.

R9: Develop a project wide strategy to identify passive measures supporting a successful resonance control.

Q4: R&D Program: Is the R&D program proceeding satisfactorily toward a construction start near the end of the current decade?

- The linac R&D program is progressing according to schedule. It should allow for a well-informed decision on construction during the Fiscal Year 2019.

- More information will be needed for the rings (see recommendation R1-4).

Q5: R&D Program: Which elements are considered as highest priority if funding is limited?

- PXIE is essential for demonstrating the operation of the low energy accelerating structures and testing other equipment like RF amplifiers, LLRF and beam instrumentation.
- Because of the long development time, work on the HB650 cavities and cryomodule has to proceed at the foreseen pace that is just compatible with a start of construction in 2019.
- The demonstration that the combined effects of tuning control and LLRF can stabilize the field in pulsed cavities at the level of 0.1% - 0.1 degree is important.
- The development of a single type of beam profile monitor would be sufficient.

Less urgent:

- SSR2 development can wait to benefit from the lessons from SSR1.
- The development of a prototype new RF cavity for the Booster and the RR can be delayed until early 2017.

3. Complementary observations and reactions

Global concept

Findings

Neutrino physics is confirmed as the main priority for FNAL's scientific program. The PIP-II project presently in preparation is a key component for that purpose. Aimed at increasing the flux of neutrinos at the start of LBNF (2024) by bringing the beam power at 120 GeV above 1 MW, it will also support the current 8 GeV program including Mu2e, g-2, and short-baseline neutrinos.

In the longer term, the upgraded accelerator complex is expected to allow for:

- upgrading Mu2e performance reach
- increasing beam power to LBNF beyond 2 MW
- operating at high duty factor/higher beam power at intermediate energies.

The PIP-II project is based on the following components:

- construction of an 800 MeV superconducting pulsed proton linac injecting in the Booster at twice the present kinetic energy,
- increase by 50 % of the beam intensity per pulse from the booster and increase of the repetition rate up to 20 Hz,
- upgrade of the RR and MI to allow slip stacking, capture and acceleration of 50 % more protons per pulse.
- making the superconducting linac extendible to support >2 MW operations to LBNF and upgradable to continuous wave (CW) operations.

PIP-II is expected to be approved as a DOE project (CD-0) in the course of 2015 with construction starting in 2019 (CD-3). Until 2019, PXIE and SRF are the major elements of the R&D program.

The major part of the cost will be supported by the DOE (491 M$), but a significant fraction will be borne by external partners (160 M$).

Observations

The recommendations issued by the Committee in 2014 have been taken into account and commented. The integration of PIP-I into PIP-II is a well-justified decision, which reduces investments in the present linac.

The need to prepare the possibility in the long term to operate the linac in CW is formally confirmed and is an integral part of PIP-II.

The R&D on linac components is productive and will properly demonstrate the capability and commitment of the Indian partner.

Linac design

The Linac design is convincing and the prototyping effort is adequate for reaching the performance goals. The low beam current simplifies beam dynamics. Some Linac-specific optimizations and design checks are however recommended and listed below.

Findings:

The RFQ is designed to produce an equipartitioned beam to avoid longitudinal/transverse emittance exchanges and the nominal beam dynamics is designed for low loss (equipartitioned, smooth phase advance transitions across structure changes) following state-of-the-art guidelines.

The prototyping and R&D program for cavities and RF sources is advancing well and the results are promising. The PIP-II team recognizes a number of challenges and risks in the design and addresses them with targeted R&D effort as follows:

Perceived challenges:

a) 5 new types of SC cavities;
b) microphonics/Lorentz Force Detuning (LFD) suppression, reliable operation of SC linac in pulsed regime;
c) a reliable CW RFQ;
d) bunch by bunch chopping;
e) high-power beam deposition in MEBT absorber which risks polluting the following HWR section;
f) longitudinal stability of 10^{-4} at the end of the linac.

Proposed solutions:

a) to continue prototyping with high priority;
b) continued R&D on tuners followed by tests in PXIE;
c) the RFQ delivery is expected in summer 2015 and first beam tests are likely to take place before the end of 2015; use of a long LEBT to eliminate gas flow from source to RFQ;
d) a low RF frequency for the front-end allowing a longer chopper rise time: chopping at low energy (2.1 MeV) reduces the required chopper gradient; the system is already under test in PXIE;
e) there are 2 m of clean space in the MEBT before the HWR but in other machines people are using ~15 m (time for a vacuum valve to close); it was already demonstrated at other labs that a relatively short distance works; however a concern remains about the proximity of the MEBT absorber to the HWR section; the set-up will be tested in PXIE;
f) a tight control of cavity phase and amplitude throughout the linac (0.1 deg, 0.1%); dumping the first 10-30 μs of each pulse reduces the variations during the beam pulse.

Comments:

Due to the low currents and low space charge the transverse beam dynamics is relatively simple.
The absence of a harmonic relation between the linac frequency (162.5 MHz) and the booster RF frequency at injection (44.7 MHz) requires a flexible chopper system, which can chop 1 or 2

bunches to enable low-loss injection into the booster. While this makes the chopper more challenging it is helpful for longitudinal painting at ring injection.
The requirements for longitudinal jitter at the linac end are very demanding. Yet we have not seen any simulations on the propagation of RF errors. These should consider the amplification of phase errors through the drifts in the MEBT and they should take into account the frequency transitions. At present there is a universal specification for RF errors in the cavities (0.1 deg, 0.1%). Revise if tighter specifications are needed for the 162.5 MHz systems or if they can be relaxed for the 650 MHz part.

The present plan is to re-use the Tevatron cryoplant, but due to its very poor efficiency the possibility to re-use the cryoplant of the CMTF should be considered as well as the option of using a new state-of-the-art cryoplant.

A very careful design of the instrumentation in the intersections is required since all installations in these areas need to be essentially particle free. As a general comment with respect to vacuum systems close to SC modules: think carefully about pumping and venting procedures as the pumping/venting speed has to be sufficiently low to avoid particle transport. At pressures above ~ 1 mbar any particle released from the surface of the vacuum chamber by movement/knocking etc. will not immediately go back to the surface but can and will be travelling.

The vibration sensitivity of the SC cavities was mentioned several times. From later talks it was obvious that so far not sufficient communication is established between the accelerator designers/builders and the civil construction experts. The Eigenfrequencies of the cryomodules are important and also the type of support that is used for installation. Consider if there are any special civil construction measures needed to reduce vibrations.

Related to the strong transverse focusing of the SC structures is the alignment of the cavities. Alignment specifications should be given and are needed for the CM design. A complete set of numbers for all SC cavities and magnets needs to be established.

Linac design recommendations:

L1: Specify "particle free" conditions for the last part of the MEBT.

Make sure that all work packages involved in the design of this last MEBT section have the full and the same understanding of the cleanliness required. This section needs to be as clean as the SC cavities itself, i.e. assembly has to take place in a clean room and local connections are to be made using local clean rooms. All components in this section should be discussed with SRF vacuum experts already during design phase. Avoid designs, which are not suited for proper cleaning. Use the wording "particle free" to enhance sensitivity.

L2: Evaluate the risk related to the single window RF power coupler design of SRR1.

L3: Consider measures to reduce the filling/decay times in the cavities for pulsed operation

Consider using a coupler matching with reduced QL, which can be increased for CW with stub tuners, if needed. Alternatively consider adjustable power couplers or the use of higher RF power to decrease the cryogenics duty cycle.

L4: Translate the needs for mechanical stability of cavities and cryomodules into functional specifications for the civil engineering design (if needed).

Rings

Findings

The main objective of PIP-II, which remains unchanged since the last Review, is to bring the beam power from the MI up to 1.2 MW. This will be achieved by increasing the intensity per pulse in the MI, RR and Booster by 50%.

Main challenges have been identified since the last Review. This result has to be obtained without increasing the beam loss power, hence by reducing the percentage of loss in all machines although the intensity will be larger. This is made even more severe considering that the Booster will operate at 20 Hz repetition rate. The RR and MI have to deliver 50% more intensity while maintaining the same loss from slip stacking, requiring the stacking efficiency to increase to 97% from 95%, and requiring tighter beam specification out of Booster. To reach that goal, it is estimated that the longitudinal emittance of the Booster bunches shall be 2/3 of that which is currently achieved, increasing further the challenge.

A new Booster injection layout is presented accepting beam at 800 MeV from the Linac. The engineering design is not yet completed.

Comments

The efforts required to reach the necessary beam characteristics with the existing synchrotrons shall not be underestimated.

The responses to Recommendations 5, 6 and 7 in the 2014 Committee report show that work on these subjects is not sufficient. For example, on plans for consolidation in RR and MI based on an exhaustive and quantitative analysis of the risks (R4), a list of hardware subsystems starts to be identified including RR Vacuum, MI quad spares, and MI power supply transformers. However, no comprehensive analysis was presented. On demonstrating with realistic simulations that slip stacking in RR at high intensity can be achieved with the acceptable loss budget (R5), simulations with Synergia including realistic apertures and transverse space charge were started but no conclusive results were presented. On testing production and preservation of low emittance bunches in the Booster and their capture in the MI at the highest possible intensity proceeding with extensive simulations and benchmark results with experimental observations (R6), the work is limited to the current intensities.

The possibility to reliably accelerate 50% more intensity per pulse in the booster with bunches of reduced emittance of 0.08 eVs remains to be demonstrated, either through specific experiments or by simulation. The same question applies to the MI that is also expected to reliably accelerate 50% more intensity per pulse. Considering the significant increase of intensity in the ring accelerator chain, a comprehensive beam dynamics analysis is necessary identifying performance limiting mechanisms and parameters including effects of space charge, wall impedances and electron cloud.

Performance of slip stacking in the RR with 50 % more beam intensity and at constant beam loss power is a major uncertainty. ESME based simulations shall be used with caution, due to the lack of clarity of the employed algorithm.

Moreover, the present goal to increase the slip stacking efficiency from 95 to 97 % is only valid if the Main Injector sends beam on target at 120 GeV. If the Main Injector cycles twice as fast to 60 GeV, the number of protons per second has to double and slip stacking efficiency has to be increased to 98.5% to keep the beam loss at the present level. This is probably an unrealistic goal.

Computer simulations need to be performed with codes benchmarked and verified. During the past couple of decades, major collaborative efforts have been made at institutes like ORNL, BNL and J-PARC. We encourage the FNAL team to take advantage of the community efforts in codes benchmarking.

Transition crossing in the MI using first order gamma-t jump is likely to be highly effective. However, similar gamma-t jump scheme is difficult to be implemented in the Booster. Experiences at RHIC and BNL AGS indicate that RF gymnastics are often inadequate in improving transition efficiency in the presence of chromatic nonlinearity, collective effects and electron cloud. Simulations with credible codes and relevant parameters are necessary along with experimental verifications.

Recommendations

R1: Perform a comprehensive beam dynamics analysis to identify performance-limiting mechanisms and parameters including the effects of space charge, wall impedances and electron cloud in the Booster, RR and MI.

R2: Assess Booster transition-crossing performance with benchmarked simulation codes.

R3: Demonstrate with realistic simulations that slip stacking in RR at high intensity can be achieved with the acceptable loss budget. Identify the resulting requirements for equipment and for the beam from the Booster.

R4: Identify and exploit a code of higher quality than ESME. Else trigger the development of a better code jointly with other concerned laboratories (CERN, SNS, J-PARC, GSI, BNL …).

PXIE and RFQ

Findings

The warm front end performance requirements (no significant changes in scheme or specification) are the following: energy 2.1 MeV, peak current up 10 mA, 5 mA nominal, pulse length microsecond to CW, bunch by bunch chopping capability, output rms emittance: $e_{\perp}<0.23$ μm, $e_L<0.31$ μm, and proper vacuum, tails, and bunch extinction management.

Status:

> Ion Source and LEBT installation are almost complete except for dipole magnet for second ion source. Ready for RFQ installation; Twiss parameters are close to those needed for the RFQ but drifting for unexplained reason.
>
> RFQ construction is progressing according to schedule. Delivery for RFQ and its input coupler are expected in June 2015. Both 75 kW power amplifiers for RFQ are commissioned to specifications and are operational.
>
> All the magnets for MEBT will be delivered in FY 16 except for two doublets with dipole corrector sets for RFQ commissioning which will be delivered this fiscal year. All power supplies for MEBT magnet will be installed at CMTF by summer 2015. Half size prototype (50-ohm) chopper kickers have been assembled and tested in vacuum with 250MHz amplifier with excellent delay of 21.97+/- 0.1 ns. Power testing of full prototype at 162.5 MHz will occur this summer. The MEBT absorber was tested successfully with an e-beam of comparable power density. The prototype buncher cavity is under test and five 3 kW amplifiers have been ordered. For RFQ characterization 2 toroids, 2 BPM, 1 scraper and a fast Faraday cup will be ready by summer.

Comments

Good progress has been made in the commissioning ion source and LEBT. The short lifetime (300 Hours) of the ion source is an issue. Continuation of R&D to increase this lifetime is encouraged.

Last two meter of the MEBT (the differential vacuum section), which accommodates beam absorber (very hot surface) needs more careful design considerations. Ion pumps should be avoided in this section.

The parallel development of two versions of kickers has been continued. The committee endorses a choice of technology to be made after tests with beam.

The beam commissioning plan for RFQ and MEBT to measure all beam characteristics except momentum spread looks reasonable.

PXIE will be an ideal platform to assess equipment performance and beam dynamics but also to test the final configuration of LLRF, modulators, high-power RF, control system, interface for operators, etc.

Recommendation

R5: Use PXIE to debug the combined operation of systems. This will save time during the actual PIP-II commissioning.

CMTF

Findings

CMTF will house PXIE and cryomodules test facilities and their infrastructures. Half of the PXIE cave (IS, LEBT, RFQ, MEBT) has been assembled and alignment network is established within the building and PXIE cave. PXIE racks, tray and power distribution are in place. Cleanrooms of class 10, 100, 1000 are operational.

Compressed air system (95 CFM, 100 PSIG, 40 deg dew point) is installed and commissioned. LCW system (1000 GPM, 100 PSIG, 83F+/- 1F, 1200 kW) is being installed. New Superfluid refrigerator (40K, 4.5K, 2K, 250w @ 1.8 K or 500W at 2k) and SLAC CTI-4000 refrigerator (1500 W @ 4.5K) will provide independent operation of PXIE and CMTF.

Comments

Completion of LCLS-II cryomodules testing is presently planned for September 2018. Any delay on the LCLS-II program will impact on the planning of test of the HB650 cryomodule, which is foreseen immediately after.

SRF

Findings

Motivated by world-wide collaboration and due to the participation in several R&D efforts and projects, Fermilab has become a key player in the field of SRF. Existing full-scale infrastructure can be offered to PIP-II, partly only after the Fermilab LCLS-II contribution. PIP-II R&D can take advantage of vertical and horizontal test areas; some of them to be extended. Using the expertise of Fermilab teams in cavity, coupler and cryostat construction, in cryogenics, and in SRF related LLRF controls, Fermilab wants to capitalize on the successful work during the last decades.

State-of-the-art work was done in cavity testing and cryomodule (beta=1) assembly. On top of this, the still relatively recent high Q discovery through Nitrogen doping has started to get a very important role in the Fermilab contributions to projects like LCLS-II, and now PIP-II R&D. Furthermore, cool-down with proper temperature gradient across cells through the transition temperature is studied since it expels the ambient DC magnetic flux and thus further reduces RF losses. Higher Qs will allow for higher duty factors, or a reduced cryogenic load in CW operation.

Development of a suite of SRF structure prototypes has been underway for the last years. The PIP-II R&D presently emphasizes now the building of prototypes for all cavities and one module each (HWR, SSR1 and SSR2, low-beta and high beta), for the lowest beta as continuation of the successful collaboration with ANL. For all other structures collaborations with Indian institutes were started.

The HWR for PXIE are under the responsibility of ANL. Assembly of the cryomodule, off-line testing (warm/no power rf), delivery to Fermilab and installation at PXIE is foreseen for FY17. Convincing work describing this world-wide first 2K HWR module was presented. So far two prototype HWRs were completed and successfully tested. The testing included the operation of the prototype solenoid and the slow frequency tuner installed on the cavity. Intentionally quenching the cavity with the solenoid fields on had no negative impact on the cavity performance. All remaining cavities are under production. The tunable rf power coupler was successfully tested; no multipacting or excessive heating were observed. After assembly at ANL the cryomodule will be cold tested at Fermilab.

The SSR development emphasizes SSR1. The schedule aims for a completed module in May 2017. Cavity production is well advanced. One cavity is leading in order to allow for coupler and frequency tuner qualification. The first cold test in a horizontal cryostat just started and is currently ongoing. In general, vertical testing successfully qualified the cavity production. Many of the cryomodule components were received. Focusing elements, support posts, and the strong-back were shown during the lab visit. The alignment of the beam line components within 0.5mm will be checked using viewports; obviously no stretched wire system is planned. The design work on SSR2 is learning from first comparison of SSR1 measurements with simulations. Recent design changes try to reduce the multipacting.

The R&D program on elliptical cavities emphasizes the HB650 cavities. Existing infrastructure is extended to go from single cell to 5-cell cavities. EP and HPR infrastructure to be finished in due time will allow for the first surface treatment of existing multi-cell cavities, which were built some time ago. Two vertical test stands are ready to take cavities. First N-doping studies were made on single cells. Results are promising since not only Q increase by N-doping was observed, but the Q dependence on the cool-down speed seems to be strongly reduced compared with the previously studied 1.3 GHz cavties. This is very promising for Q retention in the cryomodule. The driving milestone for the HB650 program is the prototype module ready in FY2018.

Observations

The finished module will be installed at PXIE. The plan of having a dust-free beam vacuum system up- and downstream of the module was mentioned. In order to guarantee long life-time of the HWR module, the vacuum system needs to be carefully designed. The neighborhood of beam diagnostic elements needs careful investigation. Out-gassing of components requires adequate pumping. Under all circumstances, the flow of particulates towards the HWR module must be avoided. An acceptance procedure used already during the design phase of all vacuum components can be useful.

The SSR1 RF power coupler uses a single warm (Nitrogen temperature) window while many other RF couplers aim for an increased vacuum safety using a two window design.

The HB650 R&D program relies somewhat on the existing multi-cell cavities produced already some time ago. The impact of a hopefully unlikely disappointment after first surface preparation is not clear. The procurement of further prototype cavities would have a non-negligible budget impact.

International Collaboration

Findings

The PIP-II R&D program is strongly based on international collaboration with several Indian institutes. The DOE-DAE Collaboration aims for two-way support of high intensity accelerator projects in the U.S. and in India. In India, both RRCAT and BARC are aiming for >MW proton linacs which have strong similarities with the 800 MeV PIP-II design. Thus the mutual interest.

The foreseen contribution to the PIP-II realization is enormous. A total of 160M$ is foreseen corresponding to approx. 25% of the total project cost, and an even larger fraction of the accelerator cost. Thus the success of the started common R&D program is of utmost importance.

Four Indian institutes are working on the development of the required s.c. systems. Collaboration with Fermilab is managed by regular meetings and reviews on different project levels. For the next future SSR1 and LB650 cavities are under fabrication in India, and FNAL will take care of surface treatment and testing. At RRCAT a large SRF facility is under construction.

Fermilab strongly relies on the contribution of RRCAT to the horizontal test program. A horizontal test stand for 1.3 GHz Modules (to fulfill the Fermilab LCLS-II obligations) is expected, and the design of a 650 MHz cryomodule test stand will immediately follow this summer.

Observations

The building of pressurized equipment using non-standard materials like Niobium requires perfect management of specifications and regulations. The fabrication of the HTS equipment will be used to establish common rules which pave the way towards future contributions to the PIP-II set-up. For the HTS set-up it bears some risk since not all interfaces are established now.

The incorporation of a really large contribution to both, the PIP-II R&D and later to PIP-II is very likely desirable. But it doesn't come without risk. The successful technology transfer requires a remarkable coordination effort. Even if successful, the schedule risk could be immense.

Recommendations

R6: Develop strategies to reduce the risk related to large in-kind contributions.

R7: As a test case, analyze and follow the risk (technical & schedule) for the HTS set-up.

Linac High Power RF

Findings

Seven types of RF power sources are planned for the PIP II linac:

- Two 75 kW, 162.5 MHz amplifier for RFQ
- 3 kW, 162.5 MHz amplifiers for 3 bunchers and for the first HWR
- 7 kW, 162.5 MHz amplifiers for 7 HWRs
- 7 kW, 325 MHz solid-state amplifiers for 16 SSR1s
- 20 kW, 325 MHz amplifiers for 35 SSR2s
- 40 kW, 650 MHz amplifiers for 33 LB650
- 70 kW, 650 MHz amplifiers for HB650

A number of amplifiers and components have already been tested. Troubles were encountered with many components. Typical is the case of the two 75 kW, 162.5 MHz amplifiers which took 6 months to commission because of water leaks, modules failures, faulty control interface, etc.

Another illustration is the 75 kW, 162.5 MHz circulators, which need to be at 83 degrees F to operate instead of the specified temperature of 95 degrees F.

Five 3 kW, 162.5 MHz amplifiers and circulators were ordered in September 2014 and delivery is expected late March 2015.

The possibility to drive a superconducting cavity with a phase-locked magnetron was demonstrated with a commercially procured 2.45 GHz 1.2 kW magnetron during a one-week test period in July 2014. The next test is planned with a 1.3 GHz magnetron procured through an SBIR–supported company. The ultimate goal is 650 MHz.

The 650 MHz amplifiers for the PIP-II linac could be solid-state or use IOTs or magnetrons. The decision will be taken in Q3FY17.

The first 3 kW 325 MHz amplifier delivered in August 2014 failed after 2 hours of operation. A replacement module is needed as well as very detailed interface and specifications. More contributions are planned to come from India.

Comments

The troubles encountered during the tests are not uncommon for prototyping or during an R&D phase. Analyzing the reasons thoroughly and taking measures is essential to improve the performance.

Interfacing documents, for example communication protocol, interlocking, etc. are also important.

The Committee encourages debugging and long run operation well before high power tests or commissioning to minimize the risk of delaying the project.

Linac LLRF and Resonance Control

Findings

The LLRF systems are planned to be developed in collaboration with India.
Resonance control of the PXIE RFQ will be obtained by adjusting the vane and wall temperatures.
Stabilizing the beam energy of the PIP-II linac at the level of 1E-4 will require the LLRF to stabilize the cavities field at the level of 0.1% - 0.1 degree combined with a beam based feedback.

Comments

Compensation of Lorentz Force Detuning (LFD) in narrow bandwidth cavities operating in pulsed mode is a major challenge for the LLRF system. In SSR1 cavities, the LFD will be of the order of 420 Hz, to be compared to the 3 dB bandwidth of 20 Hz of the loaded resonator. Algorithms have been developed to allow piezo tuners to compensate for most of the LFD and minimize the peak RF power.

In general the narrow bandwidth of the SC cavities of PIP-II requires emphasis on the issue of resonance control. Even in CW the control is challenging; in the initial pulsed mode it might become demanding. Passive measures must be exploited to reduce the load on the active control system (piezo tuner being part of the LLRF control system). Thus a project wide coordination of activities is required to identify meaningful passive measures. The need to reduce vibrations of accelerating structures to a reasonable level is mentioned elsewhere. Civil construction but also the general mechanical design of accelerator related infrastructure requires specifications or at least guidelines.

R9: Develop a project wide strategy to identify passive measures supporting a successful resonance control.

Ring RF

Findings

In the MI no additional RF voltage is required, but the RF power must be increased to permit the acceleration of 50 % more beam current. This will be obtained by installing a second power tube on each cavity.

In the RR as well as in the Booster, the RF voltage must be increased. The preferred solution is to develop new RF cavities using perpendicular bias ferrite tuners. 3-4 such cavities will have to be installed in the Booster, in addition to the existing ones. In the RR, such cavities will replace the present ones.

Comments

The development of a prototype new RF cavity for the Booster and the RR can be delayed until early 2017.

Beam instrumentation

Findings

Many types of instruments are needed for PIP-II to measure different beam characteristics at different energies. The development of the linac diagnostics is part of the PXIE project.

In the LEBT, an Allison emittance scanner and beam current monitors have been used. The Allison scanner for CW operation is being developed in collaboration with SNS and final assembly is expected in March.

The diagnostic needed for the RFQ commissioning is the immediate focus and will be available by September 2015. Beam current, position, transverse profiles, phase, energy and longitudinal bunch shape will be measured.

Prototypes of warm and cold BPMs have been developed and mapping measurement has been finished.

Fast Faraday cup for longitudinal bunch length measurement, designed at SNS, is under redesign because it damaged at HINS.

Several new non-intercepting beam instruments are planned for testing: Mode-lock laser wire for measuring both transverse and longitudinal profiles, electron beam profiler for Main Injector.

Comments

The committee heard little about the strategy of Tails/Halo measurements. This is one of the important diagnostics to mitigate the beam loss in the rings.

Prioritize the monitors, electronics, budget, as well as the resources such as FTE according to schedule.

Conventional Facility

Findings

The linac site was changed in 2014 and brought close to the booster, existing utilities and infrastructure, minimizing environmental impact on wetlands. At the same elevation as Booster and Tevatron, the linac tunnel was long enough to allow for later increasing the energy up to 1 GeV. The linac site in 2015 is slightly improved from the 2014 version to further minimize impact to existing wetland.

Electric power consumption for the PIP-II linac is estimated at 6.5 MW (including the CHL operation which serves other users).

Comments

The proposed layout is based on the standard construction practice. Further optimizations and/or justifications have to be taken into account: the CF team has to work closely with technical groups to refine building requirements such as radiation in CW operation, vibration, etc.

Re-using the existing CHL is not energy efficient: a modern installation dimensioned for the needs of the PIP-II linac would significantly reduce power consumption.

System Engineering and Integration

Findings

PIP-II engineering and integration is intended to enforce the use of the FNAL Engineering Manual for improving all engineering practice. This integrated design approach is important to follow-up equipment all along the lifetime of the facility and to optimize quality. PIP-II is a pilot project in that respect, and it faces reluctance.
The tools adopted at Fermilab for that purpose is "Teamcenter" based on EDMS.

Comments

The Committee is convinced of the importance of this approach and strongly encourages implementation. This notoriously implies extensive explanations to the engineering staff and the resources necessary for training and tutoring should not be underestimated.

Early agreement on the system engineering and integration with partner laboratories will be essential for the in-kind contributions especially those from international collaboration partners.
Well-organized document management system will become more important as the project progresses. The lessons drawn by other recent projects (e.g. XFEL) which have adopted a similar approach should be exploited.

Recommendation

R8: The Committee is convinced of the importance of a proper System Engineering and Integration and strongly encourages implementation. Early agreement on this practice with partner laboratories will be essential for the in-kind contributions from international collaborators.

Appendix1:

Charge for the PIP-II Machine Advisory Committee (P2MAC)

March 9-11, 2015
Fermilab

The Proton Improvement Plan-II (PIP-II) represents a significant step in upgrading the Fermilab accelerator complex to support a world-leading particle physics research program based on intense beams. The concept is based on a 800-MeV pulsed superconducting linear accelerator (SCL) to replace the existing 400 MeV linac, augmented by improvements to the existing Booster, Recycler, and Main Injector. The goal of PIP-II is to provide, by the middle of the next decade, 1.2 MW of beam power from the Main Injector for a long baseline neutrino experimental program, while establishing a flexible platform for subsequent development of the accelerator complex.

PIP-II is currently in the development phase with R&D activities concentrated on front-end and superconducting RF systems, supported by conceptual design activities aimed at establishing the required configuration of the SCL, Booster, Recycler, and Main Injector.

The P2MAC is asked to review the plans for PIP-II including the design concept and the R&D program. Advice and/or recommendations are sought relative to the viability of design concepts and the appropriateness of the accompanying R&D program. In particular we would like specific advice, recommendations, and/or commentary on:

1. **Design Concept:** Does the PIP-II conceptual design represent a viable concept for a high intensity proton facility meeting the enumerated performance goals?

2. **R&D Program:** Is the R&D plan properly directed at addressing the identified technical and cost risks in an effective manner? Are the risks appropriately prioritized and will the completion of the R&D plan provide a basis for proceeding to the construction phase with confidence that performance goals can be met? Is the R&D program proceeding satisfactorily toward a construction start near the end of the current decade? Which elements are considered as highest priority if funding is limited?

The P2MAC is not limited by these specific charge areas and may delve into other related areas, and offer advice, comment, or recommendations, as it deems appropriate under the general guidance of this charge. We request an oral closeout presentation by the P2MAC with Fermilab and PIP-II management, and DOE observer(s), at the end of the meeting. A written report is requested to be submitted to the Fermilab Director by April 3, 2015.

Appendix 2:

Meeting Agenda

https://indico.fnal.gov/conferenceDisplay.py?confId=9404

Monday 9 March 2015

Executive Session			
08:00	08:30	S. Nagaitsev	*Executive Session*
PIP-II Overview			
08:30	09:00	S. Holmes	PIP-II Overview: Goals, Status, and Strategy
PIP-II Design Concept			
09:00	09:30	V. Lebedev	PIP-II Design Overview
09:30	10:00	V. Lebedev	800 MeV Linac: Cold Linac
10:00	10:20		*Discussion*
10:20	10:35		*Coffee Break*
10:35	11:00	A. Shemyakin	800 MeV Linac: Warm Front End
11:00	11:25	W. Pellico	Booster Upgrades: Overview
11:25	11:50	I. Kourbanis	MI/RR Upgrades: Overview
11:50	12:05		*Discussion*
12:05	13:05		*Lunch*
13:05	14:05		*Tour of CMTF and Industrial Complex*
14:05	14:20	J. Hunt	Siting/Conventional Facilities
14:20	14:40	D. Mitchell	Engineering Activities
14:40	14:55		*Discussion*
14:55	15:10		*Coffee Break*
R&D Program			
15:10	15:35	P. Derwent	R&D Program Overview
15:35	15:55	J. Leibfritz	CMTF infrastructure
15:55	16:25	L. Prost	PXIE Warm Status
16:25	16:45	J. Steimel	RFQ Status and Commissioning Plan
16:45	17:00	J. Anderson	PXIE Operational Readiness
17:00	17:15		*Discussion*
Executive Session			
17:15	18:30		*Executive Session*
19:00	20:30		*Dinner*

Tuesday 10 March 2015

R&D Program (cont)			
08:30	08:45	H. Padamsee	Superconducting RF: Development Strategy
08:45	09:05	P. Ostroumov	Superconducting RF: HWR Status
09:05	09:35	L. Ristori	Superconducting RF: SSR1, SSR2 Status
09:35	09:55	A. Grasselino	Superconducting RF: LB650, HB650 Status
09:55	10:15		*Discussion*
10:15	10:30		*Coffee Break*
10:30	10:50	W. Schappert	Superconducting RF: Resonance control
10:50	11:10	B. Chase	LLRF
11:10	11:25	R. Pasquinelli	RF Sources
11:25	11:40	V. Scarpine	Instrumentation
11:40	12:00	S. Mishra	International Collaborations
12:00	12:15		*Discussion*
12:15	13:15		*Lunch*
Executive Session			
13:15	14:15		Followup questions/discussions as requested by the Committee
14:15	18:00		Executive Session

Wednesday 11 March 2015

Executive Session and Closeout			
08:00	11:00		Executive Session
11:00	12:00		Closeout
12:00			Adjourn